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**The Naval EarthMap Observer
(NEMO) Program and the
Naval Space Science and
Technology Program Office**

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ABSTRACT

In February 1997 the Chief of Naval Research chartered the Naval Space Science and Technology (S&T) Program Office, at the Office of Naval Research, to operate as the central point of contact for the Department of the Navy's (DON's) S&T activities in space. The Office was chartered to enhance the DON's space efforts through interdepartmental integration and linkage with external Department of Defense (DOD) commands and government agencies. The Office's goal is to optimize a plan for S&T coherency, synergy, and relevancy to effect technology transition to the DON's Systems Commands or Program Executive Offices (PEO's) while developing an investment strategy that accommodates and leverages the commonality of commercial and consumer thrust areas and products.

This paper will focus on the "Flagship" Naval Space S&T Program, the Naval EarthMap Observer (NEMO) Program, as one example of how the Office is executing its mission. It will discuss how, through NEMO, the Navy is able to leverage commercial industry and other US government agency requirements and resources to meet unique Naval needs. Finally, the paper will discuss the specifics of NEMO, the Navy's roles and responsibilities and how the Navy will use NEMO in its mission to characterize the littoral regions of the world.

Through the NEMO satellite system, the Navy will develop a large hyperspectral imagery database which will be used to characterize and model the littoral regions of the world. NEMO will provide images using its Coastal Ocean Imaging Spectrometer (COIS) Instrument along with a co-registered 5m Panchromatic Imager (PIC). With 210 spectral channels over a bandpass of 0.4 to 2.5 μ m and very high signal-to-noise ratio (SNR), the COIS instrument is optimized for the low reflectance environment of the littoral region. COIS will image over a 30km wide swath with a 60m Ground Sample Distance (GSD), and can image at a 30m GSD with ground motion compensation. A 10:30am, sun-synchronous circular orbit of 605km enables continuous repeat coverage of the whole earth. A unique aspect of the system is the spectral feature extraction and data compression software algorithm developed by the Naval Research Laboratory (NRL) called

the Optical Real-Time Spectral Identification System (ORASIS). ORASIS employs a parallel, adaptive hyperspectral method for real-time scene characterization, data reduction, background suppression, and target recognition. The use of ORASIS is essential for management of the massive amounts of data expected from the NEMO HSI system, and for development of Naval products. Specific Naval products include bathymetry, water clarity, bottom type, atmospheric visibility, bioluminescence, beach characterization, under-water hazards, total column atmospheric water vapor, and detection and mapping of sub-visible cirrus. Demonstrations of timely downlinks of real-time hyperspectral imagery data to the Naval warfighter are also being developed. The NEMO satellite is planned for launch in mid-2000 followed by an operational period of 3 to 5 years.

HYPERSPECTRAL IMAGING BACKGROUND

The Navy is in the midst of a fundamental shift away from open ocean deep water operations to joint littoral warfare. To support that effort, the Navy and Marine Corps need more precise information in denied areas regarding shallow water bathymetry, bottom type composition, detection of underwater hazards, water clarity, and visibility^[1]. Visible radiation is part of the electromagnetic spectrum that penetrates the water, and passive optical systems can provide these products from space.

To address the problems of the coastal ocean, NRL has been working since 1990 using the Airborne Visible/InfraRed Imaging Spectrometer (AVIRIS)^[2,3] which is operated by the Jet Propulsion Laboratory and flown on an ER-2 operated by NASA Ames. AVIRIS data provide 20 m spatial resolution and 200 spectral bands covering a 0.4 to 2.4 μ m spectral range at 10 nm resolution. In a collaborative effort with the University of South Florida, NRL has demonstrated the use of AVIRIS data to separate the chlorophyll signal from bottom reflectance in clear waters of Lake Tahoe^[4] and the turbid waters offshore from Tampa Bay^[5]. In addition, spectral signals from resuspended sediments and dissolved organics have been interpreted for the Tampa AVIRIS images^[5,6], and for suspended sediments and kelp beds for AVIRIS images of San Pedro Channel^[7]. These results lead

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to a general semi-analytical model for decomposition of the spectral signatures^[8,9].

Similar progress has been made on the land applications of imaging spectrometer data since the value of that data was first highlighted in an article in *Science* in 1985 (Goetz et al., 1985). Primarily using AVIRIS data, applications have been developed for the retrieval of atmospheric properties (e.g., Gao and Goetz, 1990) and for assessing crop status, environmental quality, and mineral exploration (e.g., *Remote Sensing of the Environment*, Vol. 44 (2-3), Special Issue on Airborne Imaging Spectrometry). In particular, mineral exploration has become a hot topic. Some of the leading scientists in this area have formed Analytical and Imaging Geophysics Limited Liability Co. (AIGC, Boulder, CO) to use AVIRIS and/or other imaging spectrometer data for mineral exploration, and they have a growing list of mining and oil company clients.

Multispectral imagers, such as Landsat and SeaWiFS, do not have sufficient spectral bands to resolve the complex spectral signatures in the coastal ocean or the spectral signatures used for mineral exploration. Imaging spectrometers do resolve those signatures and are an ideal tool to fill these requirements, but they have not been used to date because of cost and the demands of processing the data. Both these problems have been overcome in recent years.

NEMO PROGRAM BACKGROUND

In July 1997 the Naval Space Science and Technology (S&T) Office, part of the Office of Naval Research (ONR), selected the NEMO program to be its flagship S&T program. Being jointly funded by the Navy and Industry the NEMO program competed for and was awarded funding through the DARPA Dual-Use Applications Program (DUAP). The DUAP Program, is a joint program of the Army, Navy, Air Force, Defense Advanced Research Project Agency (DARPA), Director Defense Research and Engineering (DDR&E), and the Deputy Under Secretary of Defense for International and Commercial Programs -- DUSD (I&CP). It began in FY97 with the mission to prototype and demonstrate new approaches for leveraging commercial research, technology, products, and processes into military systems. DUAP promotes programs that share equally, between DoD and industry, the cost and risk of developing new technologies.

The Naval Research Laboratory, which had developed the original concept of NEMO with it's industry partner STDC, was selected by the Naval Space S&T Program Office to head up the design, development, and implementation of the NEMO program. Figure 1 shows the organization of the participants in the NEMO program.



Figure 1. Organizational Chart

PROGRAM OBJECTIVES

The primary function of the NEMO program is to develop and fly a satellite-borne earth-imaging HSI system to provide HSI data and to process the data to meet Naval and commercial requirements. The mission objectives are as follows:

- Demonstrate use of hyperspectral imagery for the characterization of the littoral battlespace environment and littoral model development.
- Demonstrate automated, on-board processing, analysis, and feature extraction using ORASIS.
- Demonstrate the value of hyperspectral data for DoD operations and commercial applications.
- Demonstrate support to the warfighter with real-time tactical downlink of hyperspectral end products directly from the spacecraft to the field.

Naval Requirements

NEMO meets the unique requirements of Naval Forces by imaging the littoral regions of the world in 210 spectral bands over a 0.4 to 2.5 μm bandpass with a very high SNR. NEMO has the goal of characterizing the dynamics of the littoral environment through the use of hyperspectral imagery and the development of coupled physical and bio-optical models of the littoral ocean. The collected images provide critical phenomenology to model the littoral environment. Specific areas of study for the Navy include water clarity, bathymetry, underwater hazards, currents, oil slicks, bottom type, atmospheric visibility, tides, bioluminescence potential, beach characterization, atmospheric water vapor, and subvisible cirrus along with terrestrial images of vegetation and soil. These data support identified requirements for Joint Strike and Joint Littoral warfare, particularly for environmental characterization of the littoral ocean and intelligent preparation of the battlespace for amphibious assault.

HYPERSPECTRAL IMAGING

Multispectral sensors image several wide discontinuous spectral bands (usually 3 to 5); hyperspectral sensors image at least 60, 10 nm contiguous spectral bands. Each pixel within a hyperspectral image contains a continuous spectrum used to identify materials by their reflectance or emissivity. This allows identification of components within a scene (i.e., types of minerals, trees, crops and health, bathymetry, composition) versus multispectral, which can only identify major features of a scene (i.e., rocks, trees, crops, water). Figure 2 gives a general description of the imaging spectrometry concept.

NEMO MISSION DESCRIPTION

The NEMO spacecraft will be launched into Low Earth Orbit (LEO) in mid-2000. The spacecraft will be placed in a sun-synchronous (97.81 degree inclination) orbit at 605.5 km altitude with a 10:30 a.m. ascending equator crossing. This orbit will provide a 7 day repeat coverage ability to allow, at a minimum, weekly access to any point on the

earth. The 10:30 a.m. orbital crossing ensures consistent image quality and minimal cloud cover.

Table 1 provides a general overview of the NEMO program mission characteristics.

SPACECRAFT PAYLOAD

The sensor complement flown on the NEMO spacecraft includes a Coastal Ocean Imaging Spectrometer (COIS) and a co-registered Panchromatic Imaging Camera (PIC). The primary challenges in the COIS design are the wide field of view (>2.5 degrees) and the very high SNR, particularly near the blue end (0.4 μm) of the spectrum required for ocean imaging. NEMO also employs NRL's Optical Real-time Adaptive Spectral Identification System (ORASIS), an automated end-to-end HSI data processing system that will significantly reduce the amount of data NEMO must transmit to the ground. Figure 3 shows the current NEMO sensor deck concept.

Coastal Ocean Imaging Spectrometer (COIS)

The present design of the COIS instrument employs a three-mirror-off-axis anastigmat (TMA), 15 cm aperture telescope and two spectrometers to image a 30 km wide ground swath at a 30 m GSD. Table 2 provides the characteristics of the HSI sensor system. The two spectrometers used in the COIS are:

1. The Visible Near Infrared (VNIR) spectrometer that disperses the 0.4 to 1.0 μm light into 60 spectral bands (10 nm wide) and onto the Focal Plane Array (FPA). This provides a resolution of 1.0 to 1.5% of the band and 60 spectral bins, and
2. The Short-Wave Infrared (SWIR) spectrometer that disperses the 1.0 to 2.5 μm light into 150 spectral bands (10 nm wide) and onto the FPA. This provides a resolution of about 0.6% of the band and 150 spectral bins. To achieve up to the 2.5 μm range, the SWIR requires active cooling by a cryocooler.

COIS provides very high SNR environmental products for imaging the low-reflectivity ocean surface. The NEMO spacecraft implements Ground Motion Compensation (GMC) sufficient to reduce the apparent ground speed by a factor of 5. This provides the required dwell time to give a high SNR at a GSD of 30 m. COIS is also capable of producing 60 m GSD, high SNR data products without GMC by using spatial binning of the hyperspectral FPAs.

Panchromatic Imaging Camera (PIC)

The PIC is a separate instrument that uses an on-axis telescope to simultaneously image the same 30 km swath as the COIS instrument onto a 6000 pixel long linear array to produce a panchromatic image in the 0.5 to 0.7 μm wavelength range at a 5 m GSD. PIC uses time-delay integration (TDI) of up to a factor of 4 to provide a very high SNR image of ocean scenes. The moderate COIS GSD matches the spatial scale of natural objects in the littoral zone, while the high resolution PIC provides simultaneous context and sharpening and supports commercial land imaging requirements. The 30 km ground swath of COIS and PIC spans the near-

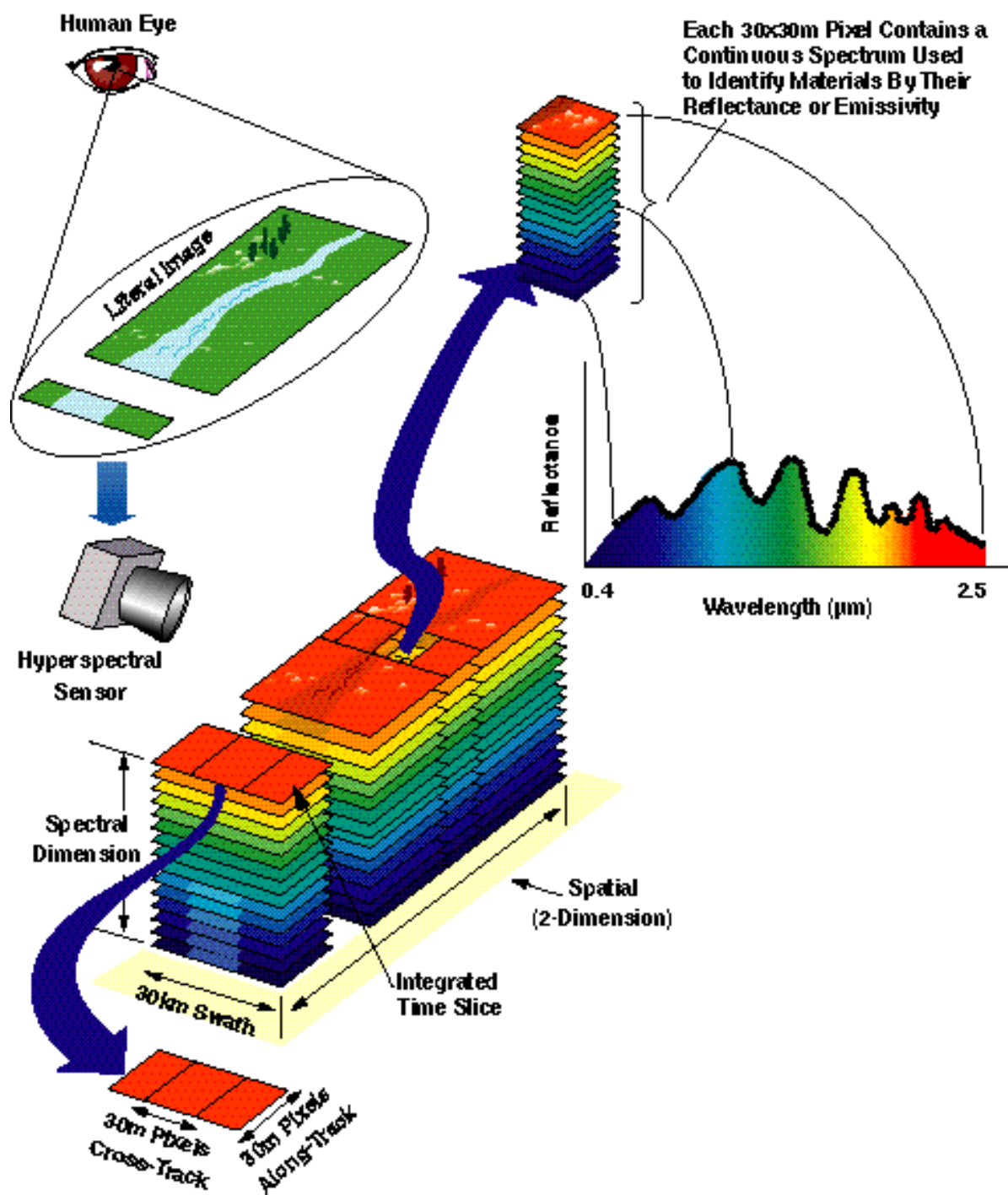


Figure 2. Imaging Spectrometry Concept

Table 1. Mission Characteristics

Item	Parameter
Launch	Mid-FY00
Orbit	<ul style="list-style-type: none"> 605.5 km sun synchronous (97.81 degrees) 10:30 am Equatorial crossing (ascending)
Repeat Global Coverage	7 day repeat, 2.5 day global average reaccess
Spectral Range	0.4 to 2.5 μm at 10 nm spectral resolution (210 bands)
Signal-to-Noise	≥ 200 over 0.4 to 1.0 μm for a 5% albedo ≥ 100 over 1.0 to 2.5 μm for a 30% albedo
Lifetime	<ul style="list-style-type: none"> 3 year mission life 5 year design life
Data Rates	<ul style="list-style-type: none"> 150 Mbps X-Band imagery and telemetry downlink 1 Mbps S-Band Imagery downlink for tactical demonstration 1 kbps S-Band command uplink
Data	<ul style="list-style-type: none"> estimated average daily imagery data ≈ 227 Gbits (storage and downlink capability of ≈ 500 Gbits) 56 Gbit on-board storage
On-Board Processing	Real-Time feature extraction and classification with $>10\times$ data reduction using ORASIS

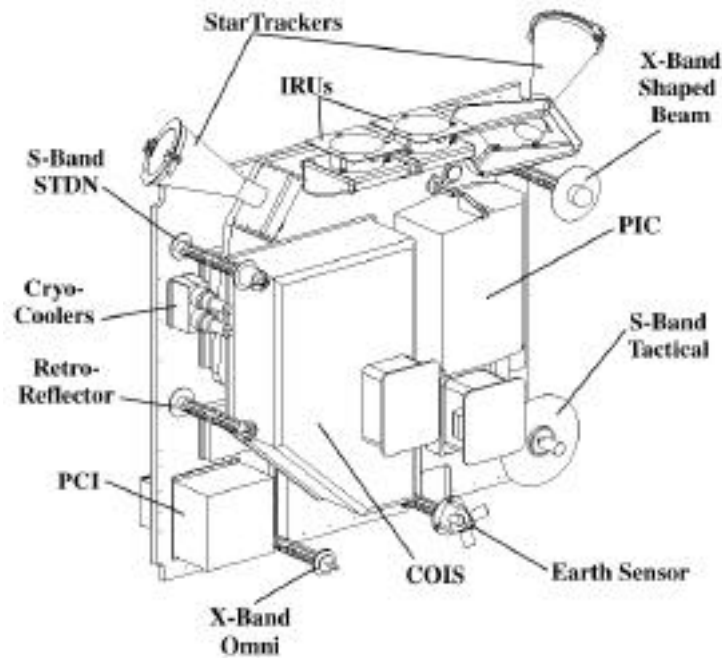


Figure 3. NEMO Sensor Deck Concept

Table 2. Sensor Imaging Payload Characteristics

SIP Parameters	COIS - VNIR	COIS - SWIR	PIC
Ground Swath Width	• 30km	• 30km	• 30km
Ground Sample Distance (GSD)/Ground Motion Compensation(GMC)	• 60m GSD at GMC-1 • 30m GSD at GMC-5	• 60m GSD at GMC-1 • 30m GSD at GMC-5	• 5m GSD at GMC 1 through 5
Aperature Diameter	• 15cm	• 15cm	• 16.4cm
Focal Length	• 36cm	• 36cm	• 120cm
F#	• 2.4	• 2.4	• 7.32
Pixel Size	• 18µm	• 18µm	• 10µm
Array Size	• 1024x1024	• 1024x1024	• 6000x1
# of Pixels/Spectral Band	• 6	• 6	• na
FPA Material	• Si	• MCT	• Si
FOV	• 2.86 degrees	• 2.86 degrees	• 2.86 degrees
Spectral range	• 0.4 to 1.0µm	• 1.0 to 2.5µm	• 0.49 to 0.69µm
Spectral Bands	• 60	• 150	• 1
On-Orbit Sparing	• 1 for 1 Spare	• 1 for 1 Spare	• 1 for 1 Spare

shore land, beach, and ocean. COIS and PIC use a single optical bench to minimize optical boresite drift. Table 2 provides the characteristics of the PIC sensor system.

Optical Real-time Adaptive Spectral Identification System (ORASIS)

The NEMO program employs NRL's automated end-to-end HSI data processing system called ORASIS. ORASIS is unique and, like the hyperspectral sensor itself, critical to the viability of the program. ORASIS offers automated and adaptive signature recognition capability, improving the operational efficiency to analyze both military and commercial data sets. It is important to note that while ORASIS is fully automated, it is also computationally intensive, requiring the NEMO satellite to have an on-board processor with GigaFLOP capability.

ORASIS is a high-speed processing system that identifies the spectral signatures corresponding to physical objects in the scene without supervision or *a priori* knowledge. The approach is to analyze each spectra in the scene sequentially, discarding duplicate spectra, and working only with the unique spectra and the map of their location in the scene. Using convex set methods and orthogonal projection techniques each observed spectrum is then analyzed in terms of the set of vectors that represent the physically meaningful basis patterns that have combined to make the observed spectrum. Then matched filters (Filter Vectors) are created and used to demix the image^[10,11].

ORASIS processing on board NEMO minimizes subsequent ground processing for data exploitation and maps of identified features, and enables the on-board production of data

products. An important benefit of ORASIS processing is a greater than tenfold data compression, relieving hyperspectral data bottlenecks of on-board data storage and transmission to the ground. An early version of ORASIS was successfully flight demonstrated in a tactical environment in the recent COVERED LANTERN exercise, using hyperspectral images from a Pioneer Uncrewed Aerial Vehicle (UAV). This test proved ORASIS compression and detection capabilities.

ORASIS is implemented on the Imagery On-Board Processor (IOBP), an advanced high speed computer consisting of a highly parallel array of digital signal processors, capable of sustaining 2.5 GigaFLOPS. The ORASIS algorithm and the radiation tolerant IOBP allow the first demonstration of real-time processing of hyperspectral data in space.

ORASIS will also be used under the NEMO program as the basic spectral decomposition tool for analyzing the HSI data and producing Naval products.

NEMO SPACECRAFT SYSTEM DESCRIPTION

System Architecture

The NEMO Spacecraft is built around a commercial spacecraft bus (LS-400) developed by Space Systems/Loral for the Globalstar communications program. The satellite is three-axis stabilized and consists of a trapezoidal main body and two deployable solar arrays.

The spacecraft system architecture consists of eight hardware subsystems plus a software subsystem, which collectively accommodate the spacecraft payload and meet the

mission and science requirements. These subsystems are: (i) the Attitude Determination and Control Subsystem (ADCS); (ii) the Electrical Power Subsystem (EPS); (iii) the Reaction Control Subsystem (RCS); (iv) the Thermal Control Subsystem (TCS); (v) the Structural Subsystem; (vi) the Mechanisms Subsystem; (vii) the Command, Telemetry, and Data

Handling Subsystem (CT&DH); (viii) the Communications Subsystem; and (ix) the Flight Software Subsystem.

Spacecraft Characteristics

Figure 4 shows a concept of the NEMO spacecraft in orbit. Table 3 provides an overview of the subsystem characteristics of the NEMO spacecraft.

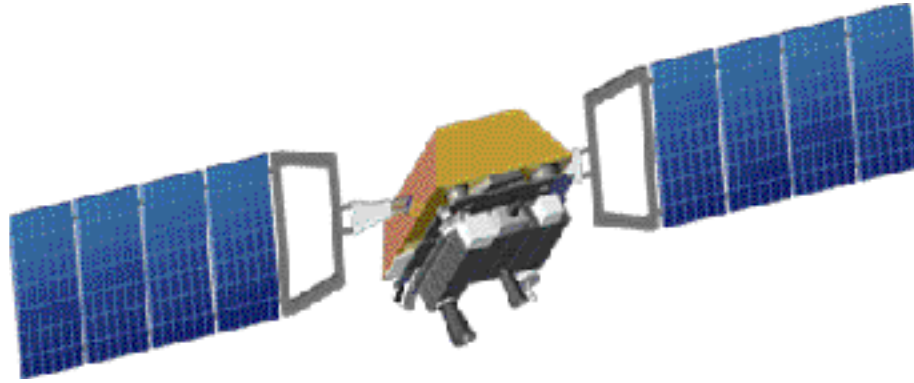


Figure 4. Spacecraft Concept

Table 3. NEMO Spacecraft Characteristics

Subsystem	Characteristics
ADCS	<ul style="list-style-type: none"> • 3-Axis stabilized for all modes; 0.07 degree control • Geolocation: 30 m with a Circular Error of Probability (CEP) of 0.9 • 2 star trackers and 1 inertial measurement unit for attitude determination • 4 reaction wheels and 2 electromagnetic torquers for attitude control
EPS	<ul style="list-style-type: none"> • 2 gimbaled (single axis) solar array panels • 4 for 3 redundant power control box • 64 Ah nickel hydrogen battery • Approximately 1500 watts
RCS	<ul style="list-style-type: none"> • Monopropellant hydrazine blowdown system • 1 propellant tank (76.5 kg capability) • 5 x 1N thrusters for orbit correction/orbit maintenance
TCS	<ul style="list-style-type: none"> • Passive thermal control with heater augmentation • Battery and payload panels thermally isolated from bus
Structures	<ul style="list-style-type: none"> • Primary structure is a combination of a rigid aluminum tubular frame and aluminum honeycomb shear panels • Kinematically decoupled optical bench • Space vehicle mass: ≈ 217 kgs dry; ≈ 295 kgs wet; payload ≈ 141 kgs
Mechanisms	<ul style="list-style-type: none"> • Optical bench launch restraints • Contamination covers for sensors • Solar array drive mechanisms for gimbaling arrays • Launch vehicle separation • Two redundant main electrical umbilical connectors

Table 3. NEMO Spacecraft Characteristics (Continued)

Subsystem	Characteristics
CT&DH Subsystem	<ul style="list-style-type: none"> On-Board Processing Electronics (OBPE) primary controller: Mongoose V (radiation-hardened processor) Payload controller: R3000 processor Imagery On-Board Processor (IOBP): multiple SHARC processors in a parallel array 48 Gb solid state data recorder
Communications Subsystem	<ul style="list-style-type: none"> Command and Telemetry Uplink: S-Band 2kbps, 2074.18 MHz Primary Imagery Data Downlink: X-Band 131 Mbps 8.2 GHz, with telemetry embedded Tactical Demonstration Imagery Downlink: S-band, 1.024 Mbps 2252.5MHz
Software	<ul style="list-style-type: none"> On-board task scheduling capability Embedded fault detection, isolation, and recovery (FDIR) Attitude control interface and functionality Spacecraft Command Language (SCL) for enhanced “macro” commanding

MISSION OPERATIONS

The NEMO program will use a combination of commercial operations and existing Defense infrastructure to provide the Naval, DoD, and commercial communities easy and timely

access to data collected by the NEMO spacecraft. The NEMO program operations concept block diagram is shown in Figure 5

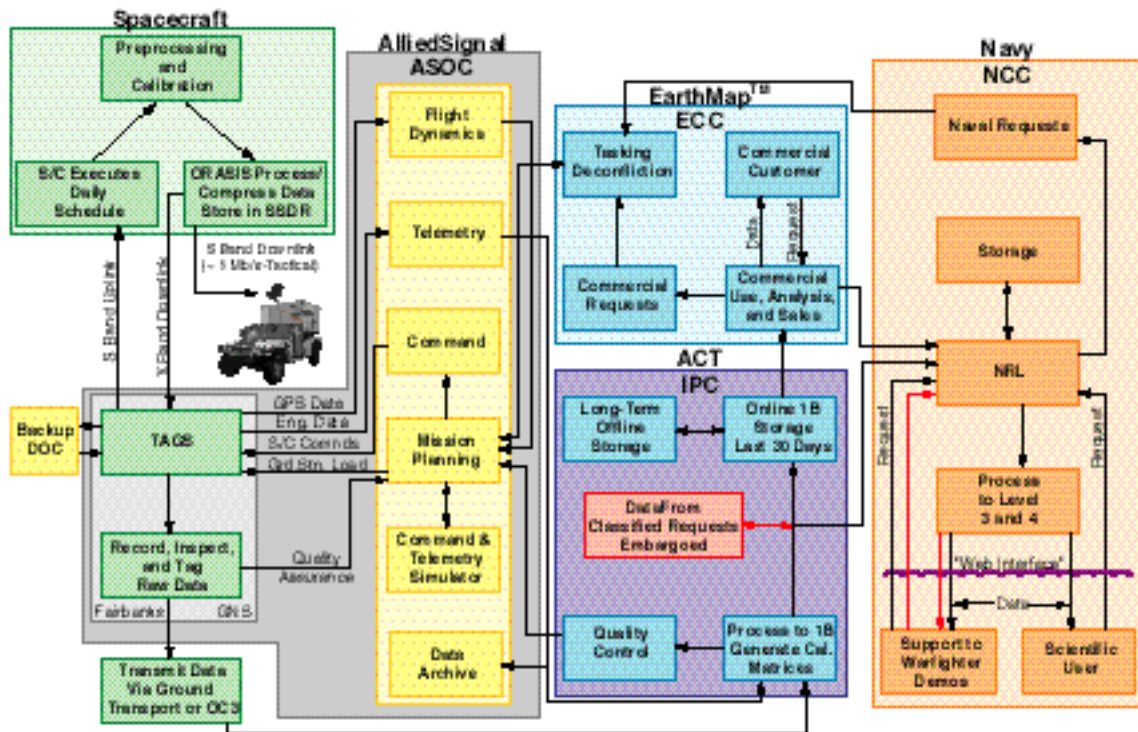


Figure 5. Operations Concept Block Diagram

Advanced Spacecraft Operations Center (ASOC)

The ASOC will be located in Columbia, Maryland and is the central hub for NEMO mission planning, S/C operations, downlink data processing, command generation, and S/C and payload state-of-health monitoring.

The ASOC communicates with the S/C through Transportable Autonomous Ground Stations (TAGS) located in Fair-

banks, Alaska, and at another site yet to be determined. The primary feature of the ASOC is that it consists of similar but enhanced elements of existing facilities. This approach effectively combines the cost savings benefits provided by reuse with the productivity enhancements of advanced technology. The ASOC also includes late-model, high-end work stations and PCs. These platforms have the capability to drive the

operation of several automated ground stations and provide simultaneous displays for multiple satellites.

Transportable Autonomous Ground Stations (TAGS)

The TAGS tracks the NEMO S/C, sends commands to the satellite from the ASOC via S-Band uplink, receives satellite health and welfare data embedded in the primary payload image data via X-Band downlink. Downlinked data is maintained on mass storage devices at the TAGS until final receipt at the Image Processing Center (IPC) is verified.

Image Processing Center (IPC)

The IPC interfaces with the ASOC to receive telemetry and imagery data. The IPC performs the image quick-look (quality control), data processing to Level 1B, and data archive functions. Activities also include fault tolerant data storage, analysis, and retrieval and in-flight sensor calibration.

NRL Control Center (NCC)

The NCC is the Naval and scientific hub for the NEMO program. The NCC performs the tasking of the NEMO spacecraft and data distribution function for the Naval segment of the mission.

TACTICAL DEMONSTRATION

Currently NEMO is being designed with the ability to downlink directly to the "field" to demonstrate the use of hyperspectral data to the warfighter. An S-Band 1 Mbps transmitter along with the IOBP and ORASIS will allow real-time processing and downlinking of data products. The current demonstration scenario is as follows:

1. The NEMO spacecraft is pre-programmed with an image target command from Fairbanks ground site.
2. The NEMO S/C enters the "demonstration area" and images the pre-programmed 30X5 km area. Imaging takes about 4 seconds.
3. In real-time the IOBP processes the image using the ORASIS processing algorithm. It first crops the image down to a 5X5 km area of interest, then processes it into an ORASIS product. ORASIS reduces a 470 Mbit raw image into a much more manageable 60 Mbit product.
4. The result is downlinked to a mobile field station via the 1 Mbps S-band antenna. This takes about 60 seconds.
5. A custom interface to the mobile field station will be provided by the NEMO team. this interface will have all the tools required to exploit the hyperspectral imagery.

SUMMARY

The NEMO program will provide the Navy and DoD with the ability to test and demonstrate the utility of environmental hyperspectral remote sensing to support the warfighter. In addition, the NEMO program along with the NEMO spacecraft provides the opportunity to apply several important technologies to dual-use remote sensing missions. These include innovations in sensors and algorithms; experience in low-cost, high-volume satellite production; experience in

small-staff, automated ground operations; and innovations in image processing and data distribution.

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